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Effects of Acoustic Ceiling Units on the Cooling Performance of Thermally Activated Building Systems (TABS)

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ABSTRACT

Europe, with a building stock responsible for about 40% of the total energy use, needs to reduce the primary energy use in buildings in order to meet the 2020 energy targets of the European Union. High temperature cooling and low temperature heating systems, and as an example, Thermally Activated Building Systems (TABS), have proven to be an energy efficient solution to provide buildings with an optimal indoor thermal environment. This solution uses the structure of the building to store heat and decrease the primary energy use.

TABS require the active (heated or cooled) surfaces to be as exposed as possible to the room, but exposing bare concrete surfaces will have a diminishing effect on the acoustic qualities of indoor spaces. Acoustic solutions capable of providing optimal acoustic comfort while allowing the heat exchange between the TABS and the room are desirable. This study quantifies the effects of two types of free hanging ceiling absorbers (horizontal and vertical) on the cooling performance of the TABS and the implications this has on the occupant thermal comfort. The measurements were carried out in a full-scale TABS test facility.

The results show a reduction of 11% of the heat removed by the TABS when 43% of the ceiling area was covered with free hanging horizontal sound absorbers at 300 mm (0.98 ft) from the active surface. This reduction was 23% for a ceiling coverage ratio of 60%. The decrease in heat absorbed by the TABS is less pronounced in the case of vertical sound absorbers for equivalent levels of sound absorption. A reduction of 12% of the heat removed by the TABS has been measured for vertical sound absorbers (equivalent sound absorption levels to 60% coverage ratio with horizontal sound absorbers). This reduction was of 13% for vertical sound absorbers (equivalent sound absorption levels to 80% coverage ratio with horizontal sound absorbers).

INTRODUCTION

A building's function is to provide a safe and healthy enclosure for people´s activities, to protect them from the outdoor environment and to provide optimal levels of comfort. On the other hand, buildings need energy to provide the right indoor environmental conditions. According to the European Environment Agency (EEA, 2001), buildings are responsible for about 40% of the total energy use in the European Union (EU). Introducing energy savings involves higher costs when the building has already been constructed. For this reason, the integration of energy savings and the use of sustainable energy resources should be a priority from the early stages of the building design. Low temperature heating and high temperature cooling systems (water-based radiant heating and cooling systems in this context) have

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proven to be an energy efficient solution for conditioning buildings (Babiak et al., 2013). In this group, Thermally Activated Building Systems (TABS) are an example of radiant heating and cooling systems. TABS' main principle is to use the thermal mass of the building to store heat and to activate the building thermal mass by embedding water-carrying pipes in the building structure. The thermal indoor environment is controlled by emitting or removing heat from the indoor space by heated or cooled TABS surfaces, and by adding or extracting heat from the TABS structure by water circulation. On the other hand, TABS require large hard surfaces to be exposed, which could have a negative impact on the acoustic quality of indoor spaces. In the case of office spaces, a productivity reduction of 67% was reported in employees working in noisy spaces (Banbury & Berry, 1998). Free-hanging ceiling absorbers can be a solution for addressing acoustic concerns; however, they will affect the cooling performance of TABS when used in combination. This study quantifies the effects of two types of free-hanging ceiling absorbers (horizontal and vertical panels) on the cooling performance of the TABS and the implications this has on the thermal comfort of the occupants.

METHODS

Details of the studied acoustic panels and layout

Two types of free hanging sound absorber units were tested. These sound absorber units were identified to be compatible with the performance of TABS (Ecophon, 2015b), i.e. they allow the heat exchange between the TABS and the room through convection and radiation (at least partially). One type corresponds to horizontal sound absorbers (Figure 1(a)), and the second type corresponds to vertical sound absorbers suspended similar to baffles (Figure 1(b)). The panels are made of high density glass wool with dimensions 1160 x 1000 mm (3.8 x 3.28 ft) and 1200 x 300 mm (3.94 x 0.98 ft) for horizontal and vertical panels respectively and a thickness of 40 mm (0.13 ft).

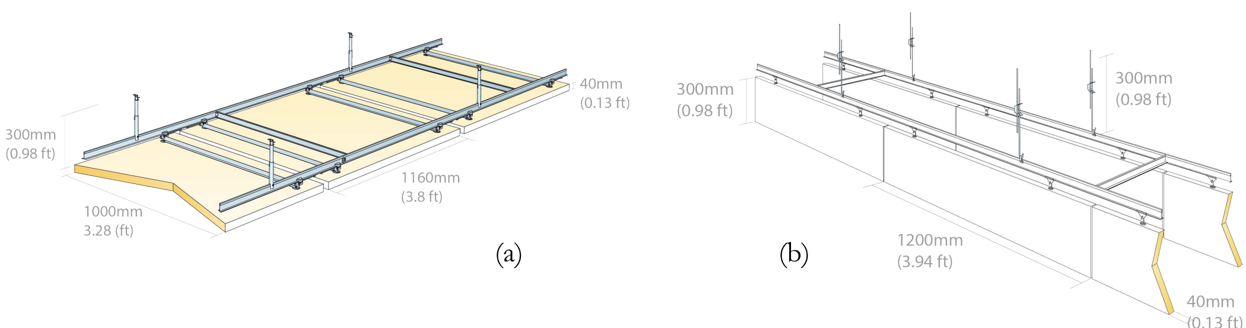


Figure 1 (a) Free-hanging horizontal panels (b) Free-hanging vertical panels or baffles.

Three scenarios were studied with free-hanging horizontal sound absorbers. The panels were installed at a distance of 300 mm (0.98 ft) from the soffit aiming for an even distribution along the ceiling area for the following ceiling coverage ratios.

Table 1. Summary of Scenarios with Horizontal Panels

Scenario	Coverage ratio	Number of horizontal panels
1a	43%	8
2a	60%	11
3a	80%	15

In the case of the vertical sound absorbers, five scenarios were studied. The panels were also installed at a distance of 300 mm (0.98 ft) from the soffit evenly spread along the ceiling area. The scenarios selected were identified as the most reasonable acoustic solutions for offices. For comparison purposes, two additional scenarios were proposed (6b and 8b) matching the sound absorption achieved with horizontal panels (Ecophon, 2015a).

Table 2. Summary of Scenarios with Vertical Baffles

Scenario	Distance between baffles	Sound absorption equivalence to	Number of vertical baffles
4b	400 mm (1.31 ft)		42
5b	300 mm (0.98 ft)	1a	57
6b	-	2a	78
7b	200 mm (0.66 ft)		87
8b	-	3a	105

In addition, a case with a bare-ceiling was also studied and used as the reference of the cooling performance of the TABS when there were no sound absorbers (Scenario 9). Figure 2 shows the different layouts with horizontal and vertical panels.

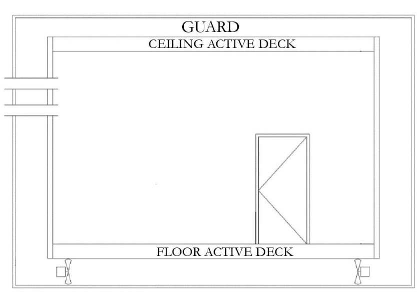
(a)

(b)


Figure 2 (a) Free-hanging horizontal panels installed in the test facility (80% ceiling coverage displayed) (b) Free-hanging vertical panels or baffles installed in the test facility (200 mm (0.66 ft) distance between baffles).

Test facility

Experiments were carried out in a test facility located at the Technical University of Denmark that resembles a room in a building with TABS. The facility consists of a 21.6 m^2 (232.5 ft^2) room with a ceiling height of 3.6 m (11.81 ft). The floor and ceiling consist of thermo-active concrete decks to attain realistic conditions of a multi-storey building with TABS. The room and the decks are surrounded by a thermal guard, whose temperature is controlled to ensure an equal temperature to that inside the room and hence avoid thermal losses or gains. Figure 3 shows the details of the test facility.

(a)


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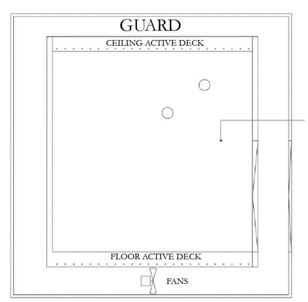

Figure 3 (a) Descriptive geometry of the test facility (longitudinal section) (b) Descriptive geometry of the test facility (transversal section)

The room has a ventilation system that is capable of providing airflow at a defined flow rate and temperature. In order to simulate the occupied period of a two-person office room, heat loads were represented by means of two thermal manikins, two computers with monitors, four light bulbs and a heating mat representing the solar heat gains from a window on a summer day. Experimental conditions are summarized in Table 3.

Table 3. Summary of the Operating Conditions during the Experiments

Constant condition	Value
Total heat loads, W/m² (Btu/h·ft2)	34.95 (11.08)
Ventilation supply temperature, °C (°F)	20 (86)
Ventilation rate, ACH	1,35
Water supply temperature decks, °C (°F)	15 (59)
Water flow rate (floor/ceiling), kg/h (lb/h)	293 (646)/283 (624)

The thermal indoor environment in the room was assessed by means of air and operative temperature (using thermocouples) as shown in Figure 4. Sensors to assess the thermal comfort of the occupants were mounted at different levels according to the recommendation in ISO 7726 (2012), which were 0.1 m (0.33 ft), 0.6 m (1.97 ft)1.1 m (3.06 ft) and 1.7 m (5.58 ft). Further information about the sensors´ accuracy and measuring range can be found in (Domínguez 2016).

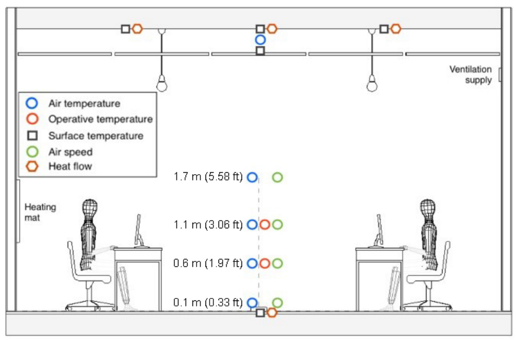

Figure 4 Position of the measurements and heat loads in the room.

Each TABS deck consisted of three prefabricated concrete decks covering the entire area of the ceiling and floor. Figure 5 shows the dimensions of the deck. PEX pipes of 20 mm (0.07 ft) outer diameter and 2 mm (0.007 ft) thickness are embedded in the concrete mass at a distance of 150 mm (5.91 ft) between the centrelines of the pipes. The flow and the supply and return temperature were measured with a Kamstrup Multical 302.

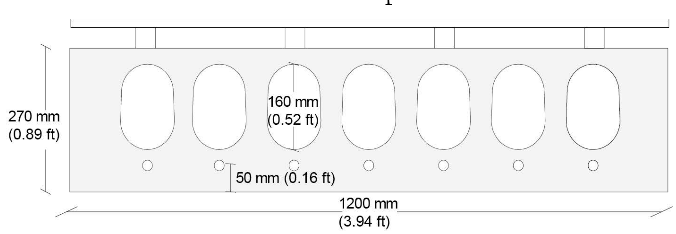

Figure 5 Descriptive geometry of one prefabricated concrete deck.

Measurements were performed under steady-state conditions, and data were obtained once the steady-state conditions were reached.

Data analysis

The focus of this study was to evaluate the effects of different scenarios with sound absorbers on the cooling performance of the upper level decks (ceiling cooling). Assuming steady-state conditions, the energy balance in the decks is found from equation (1):

$$q_{pipe} = q_{up} + q_{down} + q_{guard} \tag{1}$$

Where q_{pipe} is the heat flow in the pipe [W], q_{up} is the heat flow through the ceiling surface [W], q_{down} is the heat flow through the floor covering [W] and q_{guard} is the heat flow between the sides of the deck and the guard [W]. This latter can be neglected since the perimeter of the slab is insulated; in previous studies it has been shown that the heat loss to the guard only represents 2-3% of the total heat flows (Weittzmann, 2004). q_{up} was used to calculate the TABS cooling performance. Figure 6 shows the heat flows in the decks.

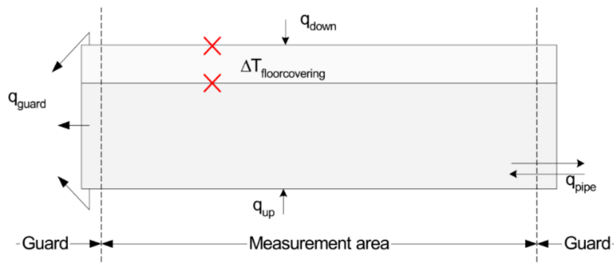

Figure 6 Illustration of heat flows in the decks (Weittzmann, 2004)

The heat flow between the pipes and the concrete decks (q_{pipe}) can be calculated from the measured water flow and the temperature difference between the supply and return water flows. q_{pipe} can be found from equation (2):

$$q_{pipe} = \dot{m} \cdot c_p \cdot (T_{supply} - T_{return}) \qquad (2)$$

Where, $\dot{m}$ is the mass flow rate of the fluid in the pipes [kg/s], c_p is the specific heat capacity of the fluid in the pipes [kJ/(kg.K)], T_{supply} is the supply temperature of the water [°C], T_{return} is the return temperature of the water [°C].

The heat flow across the floor covering (q_{down}) can be calculated form the following equation (3):

$$q_{down} = \frac{1}{R_{floor\ covering}} \cdot \Delta T_{floor\ covering} \qquad (3)$$

Where, $R_{floor\ covering}$ is the resistance of the floor covering [m²K/W] and $\Delta T_{floor\ covering}$ is the temperature difference [°C] between the upper and lower surfaces of the floor covering.

However, when assessing the cooling performance of the TABS using the cooling capacity of the active surface of the deck, it should be noted that this parameter is influenced by the temperature of the room and this is expected to vary depending on which scenario is tested. Based on these observations, Weitzmann (2004) has proven that one parameter remained almost constant for each given scenario, i.e. cooling capacity coefficient (U_{cc}). The cooling capacity coefficient of the ceiling (U_{cc}) is defined as follows (Weitzmann, 2004):

$$U_{cc} = \frac{q\ up}{A_{deck} \cdot (T_{room} - T_{fluid})} \qquad (4)$$

Where, A_{deck} is the area of the deck [m²], T_{room} is the operative temperature [°C] and T_{fluid} is the average temperature of the water in the decks [°C].Further details of the testing facility and the experimental conditions can be found in (Domínguez 2016), (Rage 2015) and (Weitzmann 2004).

RESULTS AND DISCUSSION

Figure 7 shows the cooling capacity coefficient and cooling performance reduction as a function of the ceiling coverage ratio for horizontal panels.

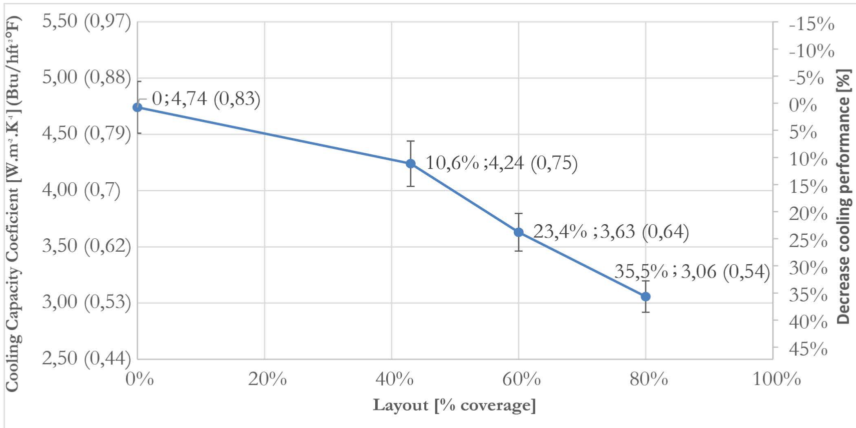

Figure 7 Cooling capacity coefficient and decrease of cooling performance as a function of the ceiling surface area covered with horizontal panels

Figure 7 shows that the cooling performance of the TABS decreases when the ceiling surface coverage increases. The heat exchange between the room and the TABS is hindered when the celiling is covered with free-hanging horizontal sound absorbers. This reduction, compared to the bare-ceiling, accounts for 10.6% with 43% coverage, 23.4% with 60% coverage and 35.5% for 80% of the ceiling surface covered with panels.

Figure 8 shows the cooling capacity coefficient and cooling performance reduction as a function of the number of vertical baffles.

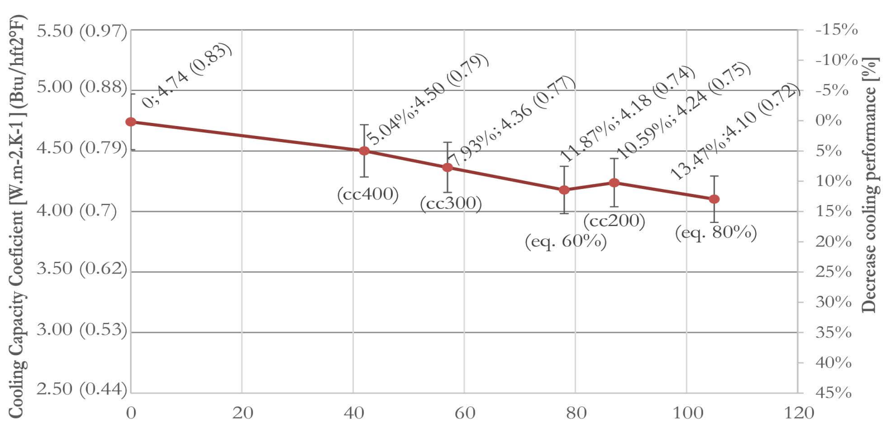

Figure 8 Cooling capacity coefficient and decrease of cooling performance as a function of the number of vertical baffles

Figure 8 shows that the presence of the vertical baffles also has an effect on the cooling performance of TABS. The cooling performance decreases as the number of baffles increases. The decrease of the cooling capacity coefficient accounts for 5% in the case of baffles at a distance of 400 mm, 8% for the scenario cc300 and 10.6% for the scenario cc200. As a consequence of the reduction in cooling performance, the operative temperature in the occupied space increases. In the case of horizontal panels, this increase was 1.5 and 1.6 K (2.70 and 2.88 ºF) for 60% and 80% coverage, respectively. In the case of the vertical baffles, the operative temperature of the room increased by 0.4 K (0.54 ºF) for cc400, 0.5 K (0.9 ºF) for cc300 and by 0.8 K (1.44 ºF) for cc200.

Figures 9 and 10 show the air temperature distribution in the room along the vertical plane.

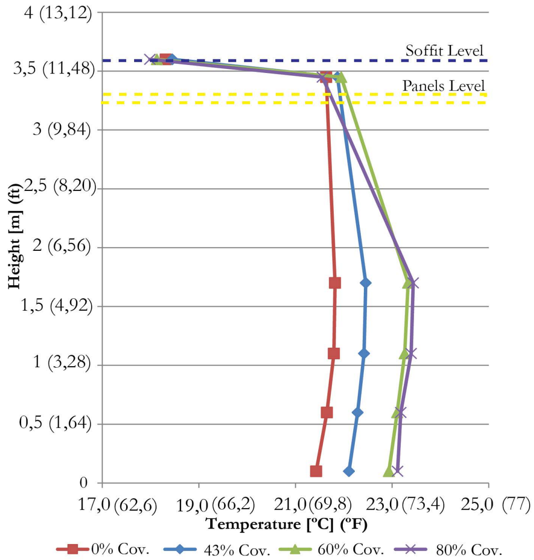

Figure 9 Measured air temperature at different heights for each scenario with horizontal panels

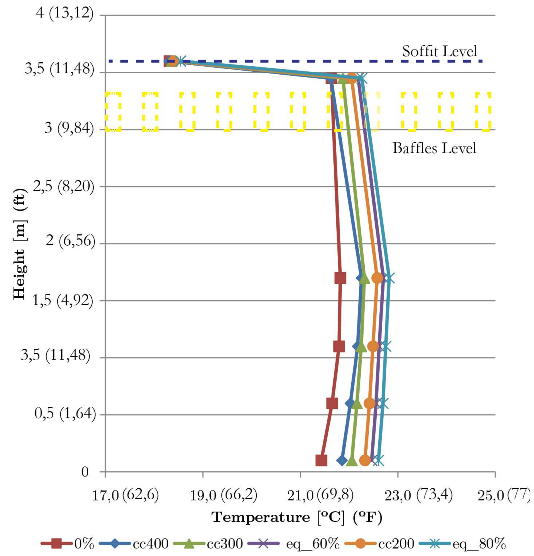

Figure 10 Measured air temperature at different heights for each scenario with baffles

As it can be seen from Figure 9, the temperature difference between the plenum space and 0.6 m (1.97 ft) above the floor level was 0.6 K (1.08 ºF) for 43% coverage, 1.4 K (2.54 ºF) for 60% coverage and 1.8 K (3.24 ºF) for 80% coverage, whereas it was 0.2 K (0.36 F) for the bare-ceiling at the same measuring points. This shows that the horizontal panels are preventing the cooled air from mixing with the rest of the air in the room; this effect becomes more evident with a higher ceiling coverage ratio. In the case of vertical baffles, Figure 10 shows that, the air temperature difference between the occupants' level and the plenum is between 0.4 K (0.54 ºF) and 0.7 K (1.26 ºF). Cold air stagnation in the plenum due to the presence of vertical baffles is not observed.

Figure 11 shows a comparison of cooling capacity coefficient between scenarios with horizontal and vertical panels.

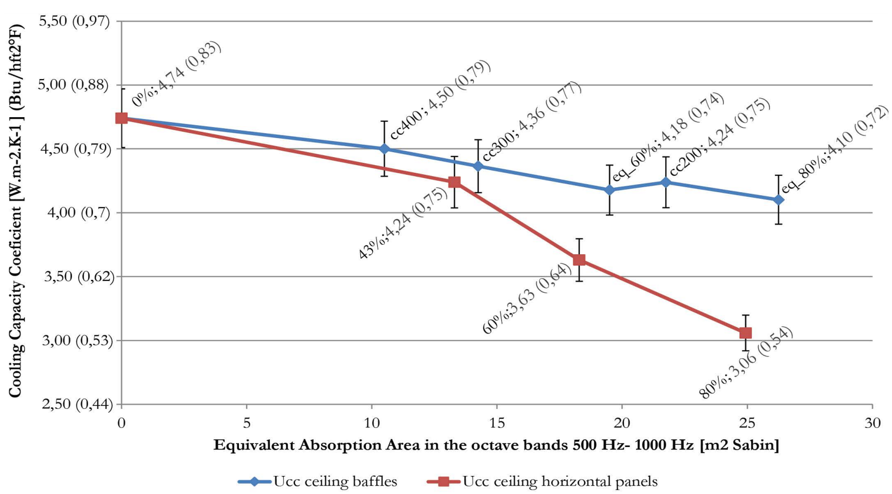

Figure 11 Cooling Capacity Coefficient of horizontal and vertical panels as a function of the equivalent sound absorption in the mid frequencies

The results show that for low sound absorption levels, the cooling performance of the TABS remains similar for horizontal and vertical panels. However, for higher sound absoption levels, horizontal panels have a higher influence on the cooling performance of the TABS than vertical baffles. The cooling performance is reduced by 23% and 36% for 60% and 80% coverage respectively for horizontal panels, while it is reduced by 12% and 13% for scenarios with equivalent sound absorption with vertical baffles. Based on these findings, and the facts that horizontal sound absorbers can efficiently absorb a wider range of sound frequencies and require less absorptive material than vertical baffles for a given sound absorption, it could be concluded that horizontal sound absorbers represent a more efficient solution when low sound absorption levels are required. When higher sound absorption levels are required, vertical baffles represent a better fit for purpose as they have a lower impact on the cooling performance of the TABS for equivalent sound absorption levels.

CONCLUSION

Acoustic comfort, as well as thermal comfort, plays an important role for human well-being and productivity. The effects of horizontal and vertical sound absorbers on TABS cooling performance in a test facility were investigated in this study.The diminishing effect on the cooling performance of TABS due to the presence of horizontal panels can be quantified as follows; 11% reduction when 43% of the surface of the ceiling is covered, 23% reduction for a coverage ratio of 60%, and 36% reduction for 80% coverage ratio. The cooling performance decrease for 43 and 60% coverage ratio can be considered acceptable, though these panels need to be combined with wall-mounted acoustic units to achieve an optimal sound absorption in the full spectrum of frequencies. Vertical free hanging units, or baffles, are a significant alternative to be used in combination with TABS. According to the measurements performed, vertical baffles have a lower impact on the cooling performance of the TABS compared to horizontal panels for equivalent sound absorption levels. A reduction of 5% on the cooling performance of the TABS has been measured when the ceiling is covered with baffles at a spacing of 400 mm (cc400), 8% reduction for cc300 and 11% reduction for cc200. For equivalent sound absorption levels to 60% coverage, the cooling performance of the TABS is 16% lower with horizontal panels compared to vertical baffles. For 80% coverage, this difference is of 25%. Cold air stagnation in the plenum has been identified as the major problem for the convective heat exchange between the TABS and the room. The masking effect of the panels, especially horizontal sound absorbers, not only prevents stagnated cold air from mixing with the room air, but also degrades the cooling performance of the TABS.

ACKNOWLEDGMENTS

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